

Paper Title: The Use of Doublers in Delamination Toughness Testing

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ABSTRACT

In this paper, the data reduction equations for common delamination toughness tests are rederived for use with specimens which have bonded doublers. The common toughness tests considered here are the double cantilever beam (DCB) for mode I toughness; the end notch flexure (3ENF) and 4 point ENF (4ENF) for mode II toughness; and the mixed mode bending (MMB) test for testing under combined mode I and mode II loading. Because the addition of the doublers changes the bending stiffness of the specimens, these data reduction equations may need to be corrected. Doublers were added to the delamination test specimens to solve a premature failure problem. Delamination toughness is normally tested using a beam with an imbedded insert so that one end of the specimen is split into two arms. If the specimen is too thin, or if the toughness of the material is too high, an arm of the specimen may fail in bending before the delamination grows. When this occurs, the toughness of the material cannot be determined. To delay the bending failure so that delamination growth occurs, doubler plates were bonded to both top and bottom surfaces of the specimen. A doubler parameter, β , which describes how much the use of doubler plates changed the ratio of full thickness to delaminated bending stiffnesses, was defined. When changes to the data reduction equations were required, the changes were minor when written in terms of the β parameter. The doubler plate technique was demonstrated by measuring the mixed-mode fracture toughness of a carbon-carbon composite using test specimens which would otherwise have failed before delamination growth occurred. The doubler plate technique may solve several problems that can be encountered when testing delamination fracture toughness.

Keywords: composite, delamination, fracture toughness, test technique, carbon-carbon

SYMBOLS

a	Crack length, in.	E	Extensional modulus, psi
b	Specimen width, in.	EI	Bending stiffness, lb-in ²
c	MMB apparatus lever length, in.	G	Strain energy release rate, in-lb/in ²
h	Half thickness of the specimen, in.	G ₁₃	Shear modulus, psi
h _D	Thickness of doubler plate, in.	P	Applied load, lb
l	Inner half span length in 4ENF test, in.	β	Doubler parameter
C	Compliance of test specimen, in./lb	δ	Displacement at the applied load point, in.
L	MMB, 3ENF or 4ENF half span length, in.	χ	Crack length correction factor

κ Relative modulus of doubler material
 λ Relative thickness of doubler

ϕ Shift in bending centroid due to doubler, in.
 Γ Anisotropy factor

Subscripts:

11,22,13 Longitudinal, transverse, or shear
 I, II Mode I or Mode II
 full, del Full thickness or delaminated beam

prop, init Propagation or initiation value
 D Doubler plate

INTRODUCTION

Delamination is a primary mode for failure of composite structures. The resistance to delamination is normally characterized by fracture toughness, and test standards have been developed to measure delamination fracture toughness under various modes of loading. The double cantilever beam test (DCB; ASTM D5528[1, 2]) is used for Mode I, the 3 point end notch flexure test (3ENF) [3] or the 4 point end notch flexure test (4ENF) [4] is used for Mode II, and the mixed-mode bending test (MMB; ASTM D6671) [5, 6] test is used for mixed-mode I/II. All of these tests use a split cantilever beam specimen loaded in bending as shown in Figure 1. However, if the material is very tough (e.g., due to through-the-thickness reinforcement) or if the laminate is thin, the arms of the delamination test specimen will fail in bending before the delamination grows [7], making a delamination fracture toughness measurement impossible. The failure of these arms normally initiates on the external surface of the specimen where the maximum compressive stress occurs. The strength of a composite is normally lower in compression than in tension, and the compression strength is particularly low at the surface of the material where the fibers have less support. The low compression strength of the composite material therefore leads to compression failure at the surface, as shown in Figure 2, before delamination extension occurs. This type of failure precludes a valid toughness measurement from being obtained from the test specimen. In mode I, a test method has been developed where tension is applied to the arms of the specimen to delay the bending failure [8], but the method is not applicable to mode II or mixed mode toughness measurement. In reference 9, bonded doubler plates were added to thin facesheet sandwich specimens so that the facesheet debond

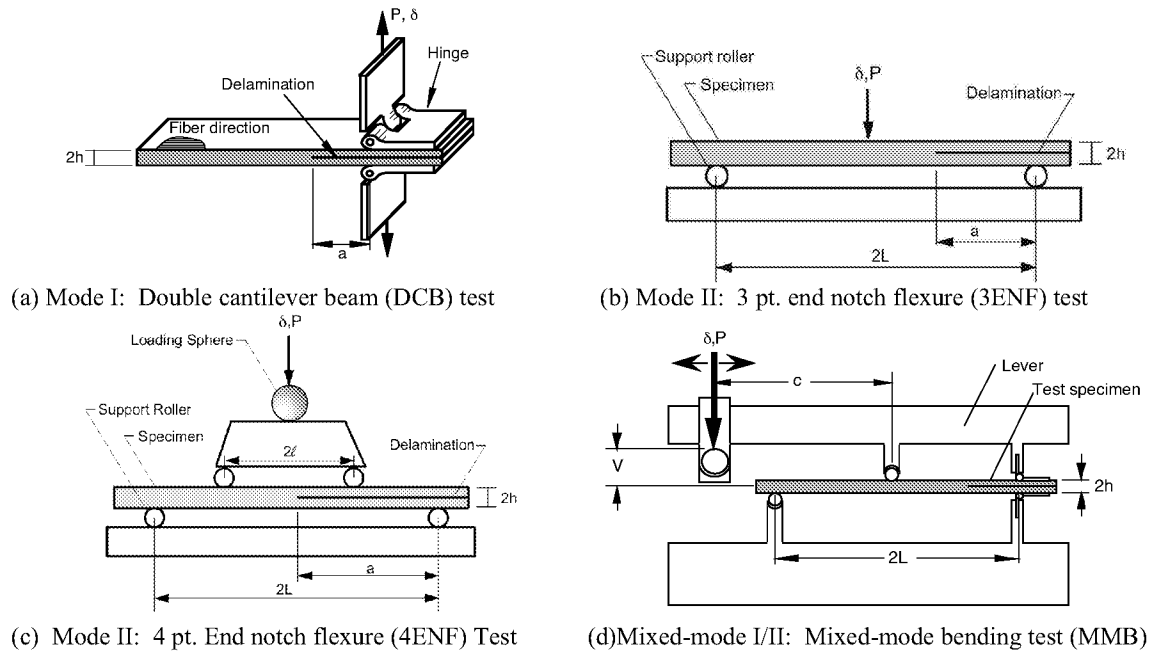


Figure 1 Delamination toughness fracture tests.

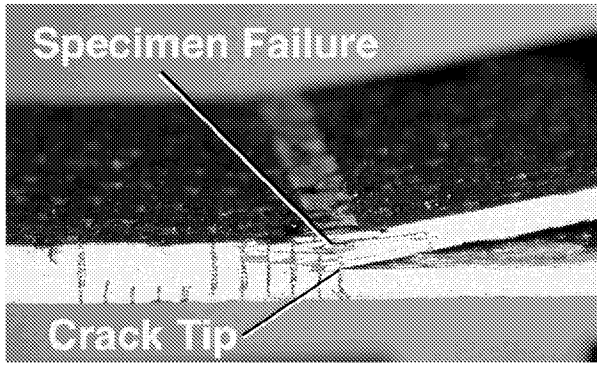


Figure 2 Failure of test specimen at crack tip.

than the composite. The effect of the doubler plate is shown schematically in Figure 3 for a DCB type test.

The use of doubler plates changes the stiffness of the test specimen and in some cases affects the published data reduction methods for a given delamination fracture test (DCB, 3ENF, 4ENF, or MMB). The data reduction methods for each test were re-derived, accounting for the bonded doubler plates. Any changes to the published data reduction equations needed when using doubler plates are highlighted.

The use of the doubler plates will be demonstrated on carbon-carbon composite test specimens, which would have failed as shown in Figure 2 without the use of doubler plates. For manufacturing reasons, these specimens were made ~0.1-in. thick, which is approximately half the thickness of specimens commonly used for delamination studies. Although DCB tests were conducted successfully, with these thin test specimens, the 3ENF and MMB tests resulted in premature failures as described earlier. The doubler plate technique will be demonstrated using these carbon-carbon test specimens and the MMB test to successfully measure mixed-mode delamination toughness.

ANALYSES

Many different data reduction methods can be used to calculate strain energy release rate from the experimental data, but all can be related back to the basic form of the strain energy release rate equation given by

$$G = \frac{P^2}{2b} \frac{dC}{da} = \frac{P}{2b} \frac{d\delta}{da} \quad (1)$$

The addition of doubler plates to the composite specimen changes the compliance, C , of the specimen and therefore may affect the data reduction equations, since these equations were derived assuming a homogenous specimen stiffness. Once the doublers are added to the specimen, the homogeneous assumption is no longer valid. Figure 4 defines the geometry of the specimen once the doubler plates are added. The critical changes are the increase in bending stiffness EI of the delaminated and full thickness portions of the beam and the ratio of these two stiffnesses.

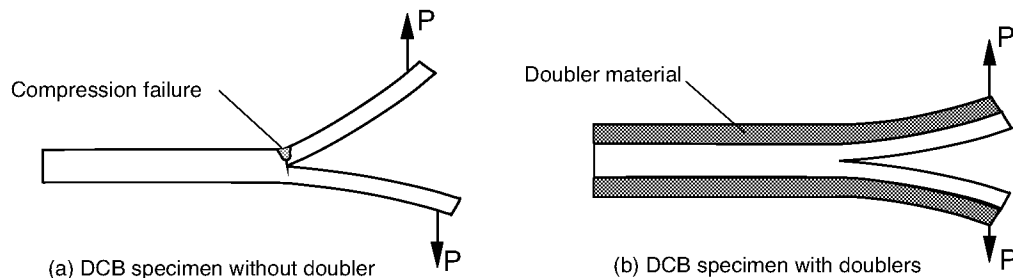


Figure 3 Diagram showing the effect of doubler plates.

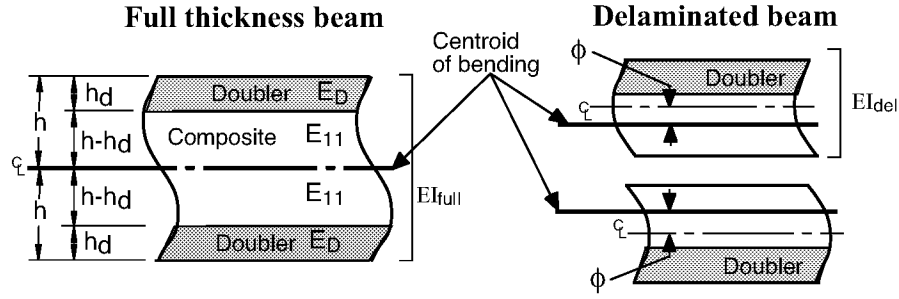


Figure 4 Notation used in the calculation of bending stiffness.

If the specimens were homogeneous, the bending stiffness of the two sections of the beam would be $EI_{full} = E_{11}b(2h)^3/12$ and $EI_{del} = E_{11}b(h)^3/12$. The ratio of the bending stiffnesses of the full thickness to the delaminated region would then be $EI_{full}/EI_{del} = 8$. In the full thickness region, a doubler is added to each side of the specimen so the bending centroid remains along the center line of the specimen. In the delaminated region, the bending centroid shifts from the geometric center of the arm by an amount, ϕ . This shift in the bending centroid complicates the calculation of the bending stiffness of the arms. Accounting for the addition of the doublers, the bending stiffnesses of the full thickness and delaminated sections can be derived from basic strength of material equations and are given by the following equations:

$$EI_{full} = \frac{E_D(2h)^3 + (E_{11} - E_D)(2h - 2h_D)^3}{12} b \quad (2)$$

$$\phi = \frac{E_D h_D \frac{(h - h_D)}{2} + E_{11} (h - h_D) \frac{(h - h_D)}{2}}{E_D h_D + E_{11} (h - h_D)} \quad (3)$$

$$EI_{del} = \left[\frac{E_{11} (h - h_D)^3}{12} + E_{11} (h - h_D) \left(\frac{h - h_D}{2} - \phi \right)^2 + \frac{E_D (h_D)^3}{12} + E_D h_D \left(\frac{h_D}{2} + \phi \right)^2 \right] b \quad (4)$$

The effect of the doubler can be different for different delamination tests or different data reduction methods for a given test. When the addition of the doubler plates does change the data reduction equation, the change can be written easily once a doubler parameter, β , is defined as given in the following equation:

$$\beta \equiv \frac{\left(\frac{EI_{full}}{EI_{del}} \right)^{doubler}}{\left(\frac{EI_{full}}{EI_{del}} \right)^{homogeneous}} = 1 + \frac{3\kappa(1 + \kappa)(1 - \lambda)\lambda^2}{1 + 4\kappa\lambda - 6\kappa\lambda^2 + 4\kappa\lambda^3 + \kappa^2\lambda^4} \quad (5)$$

$$\text{where} \quad \lambda \equiv \frac{h_D}{h} \quad \kappa \equiv \frac{E_D - E_{11}}{E_{11}} \quad (6)$$

DCB Analysis

The double cantilever beam (DCB) test measures Mode I fracture toughness. This test is shown in Figure 1(a), and is the simplest delamination test to perform, yet the ASTM standard [1] for

this test gives three options for the data reduction procedure. The options are: (1) the modified beam theory, (2) the compliance calibration, and (3) the modified compliance calibration method. Of these, the modified beam theory method is the most commonly used. The stiffness of this specimen is only affected by the bending stiffness of the delaminated region, and all three data reduction methods measure the stiffness (or compliance) of the test specimen directly. Therefore, all three data reduction methods can be used without modification when testing with doublers.

The toughness from a DCB specimen can also be calculated using a corrected beam theory method[10]. This method is presented because it will be used in the derivation of the MMB toughness calculations presented later in this paper. This calculation method starts with a simple beam theory equation for the displacement of the specimen, but corrects the displacement for shear deformation and for local deformations that occur around the crack tip, which are not accounted for in simple beam theory. These corrections are introduced through a parameter, χ , which is multiplied by the arm thickness and added to the measured crack length. The corrected displacement calculations are:

$$\delta = \frac{2(a + \chi h)^3}{3 \left(E_{11} \frac{bh^3}{12} \right)} P \xrightarrow{\text{with doublers}} \frac{2(a + \chi h)^3}{3 EI_{\text{del}}} P \quad (7)$$

$$\text{where } \chi = \sqrt{\frac{E_{11}}{11 G_{13}} \left[3 - 2 \left(\frac{\Gamma}{1 + \Gamma} \right)^2 \right]} \quad \text{and} \quad \Gamma = 1.18 \frac{\sqrt{E_{11} E_{22}}}{G_{13}} \quad (8)$$

The χ correction parameter is affected by the addition of the doubler, but this should be a small change in a minor correction factor, and therefore, this effect will be assumed negligible in this paper.

Once an expression for displacement is found it can be substituted into Eq. 1 to obtain an expression for G . For the DCB test this expression is given by the following equation, where the bending stiffness with doublers (EI_{del}) is given by Eq. 4:

$$G_I = \frac{P^2(a + \chi h)^2}{b \left(E_{11} \frac{bh^3}{12} \right)} \xrightarrow{\text{with doublers}} \frac{P^2(a + \chi h)^2}{b EI_{\text{del}}} \quad (9)$$

The equations for the three data reduction methods found in the ASTM standard can all be derived from Eqs. 7 and 9 (for some methods the crack length correction term, χh , is neglected).

3ENF Analysis

The 3-point end notch flexure (3ENF or ENF) [3] test is shown schematically in Figure 1b. This test has traditionally been the preferred test for Mode II fracture toughness, but is quickly being replaced by the 4ENF test, which will be discussed in the next section. Again there are several ways of calculating the strain energy release rate from the experimental data in a 3ENF test. The most common is the compliance calibration method, where the change in compliance with crack length is measured directly. This data reduction method requires no modification when using doublers because of the direct measurement of compliance change.

A second data reduction method is called the direct beam method. Here both load and displacement are used in the data reduction method, but the equation assumes that the change in compliance with crack length will be as predicted by a simple beam theory model of the test specimen. The original equation was derived assuming a homogeneous specimen stiffness so that the ratio of bending stiffness between the full thickness and delaminated regions would be 8. When doublers are used, this is no longer true. The modification to the direct beam theory equation is as follows and incorporates the doubler parameter, β :

$$G_{II} = \frac{9 a^2 P \delta}{2 b (2L^3 + 3a^3)} \xrightarrow{\text{with doublers}} \frac{3(4\beta - 1) a^2 P \delta}{2 b (2L^3 + (4\beta - 1)a^3)} \quad (10)$$

A third data reduction method is the corrected beam theory method[11]. This method is not commonly used for the 3ENF test, but the following equations will be used in the derivation of the MMB test data reduction method, presented in a later section. As in the corrected beam theory method for the DCB test, the derivation of this method starts with a simple beam theory model for the displacement of the specimen. To improve the accuracy of the equation, it must be corrected for deformations that simple beam theory does not model. The correction again takes the form of an addition to the crack length and again involves the χ parameter defined earlier, but for this specimen the crack length correction term is $0.42\chi h$. Because the corrected beam theory equation uses a modeled beam stiffness value, the equation must be corrected to account for the use of doublers. The correction is introduced through the β parameter.

$$\delta = \left[\frac{3(a + 0.42\chi h)^3 + 2L^3}{96 \left(E_{11} \frac{bh^3}{12} \right)} \right] P \xrightarrow{\text{with doublers}} \left[\frac{(4\beta - 1)(a + 0.42\chi h)^3 + 2L^3}{96 \beta EI_{del}} \right] P \quad (11)$$

Substituting Eq. 11 into Eq. 1, the strain energy release rate from the test specimen can be determined. The correction for the doublers found in Eq. 11 carries over into Eq. 12.

$$G_{II} = \frac{3(a + 0.42\chi h)^2 P^2}{64 b \left(E_{11} \frac{bh^3}{12} \right)} \xrightarrow{\text{with doublers}} \frac{(4\beta - 1)(a + 0.42\chi h)^2 P^2}{64 \beta b EI_{del}} \quad (12)$$

Eq. 10 can be derived from Eqs. 11 and 12 if the crack length correction term is neglected.

4ENF Analysis

The 4-point end notch flexure (4ENF) test measures Mode II fracture toughness [4]. The specimen is schematically shown in Figure 1(c) and is often preferred over the 3ENF test because it normally produces stable delamination growth. A compliance calibration method is most often used to calculate the fracture toughness from experimental data. Because the change in compliance with crack length is measured directly, no change in the data reduction equation is needed when adding doublers to the test specimen. A closed-form expression for toughness can also be derived from simple beam theory, as was done for the two previous test. This derivation also starts with a closed-form expression for displacement. However, a χ parameter correction has not been developed for this test yet, and therefore, the displacement term may not be as accurate as for the DCB or ENF tests. When doublers are used the equation must be corrected by the use of the β parameter.

$$\delta = \left[9a + 5L + \ell \right] \frac{(L - \ell)^2 P}{96 \left(E_{11} \frac{bh^3}{12} \right)} \xrightarrow{\text{with doublers}} \left[3(4\beta - 1)a + (4\beta + 1)L - (4\beta - 5)\ell \right] \frac{(L - \ell)^2 P}{96 \beta EI_{del}} \quad (13)$$

Substituting Eq. 13 into Eq. 1, a closed-form expression for strain energy release rate can be obtained as follows:

$$G_{II} = \frac{3(L - \ell)^2 P^2}{64 b \left(E_{11} \frac{bh^3}{12} \right)} \xrightarrow{\text{with doublers}} \left[\frac{(4\beta - 1)}{\beta} \right] \frac{(L - \ell)^2 P^2}{64 b EI_{del}} \quad (14)$$

These expressions can be used to confirm that values from the compliance calibration method are of the right magnitude.

MMB Analysis

The mixed mode bending (MMB) test [12, 13] is shown in Figure 1(d). This test measures delamination fracture toughness under combined Mode I and Mode II loading and is an ASTM standardized test [5]. The MMB test has advantages over several other mixed-mode tests such as specimens from the same composite panel may be used to obtain Mode I, Mode II and mixed-mode toughness values and closed-form equations can be used to separate the mode I and mode II components of fracture toughness. The mixed-mode ratio also stays reasonably constant as the delamination grows.

The MMB test uses a lever to simultaneously apply, to a unidirectional test specimen, loadings similar to the DCB and 3ENF tests. Mixed mode ratios of G_{II}/G_I between 20% and 100% can be measured by adjusting the lever length, c . When calculating G from experimental data from the MMB test, a compliance calibration technique is not used because delamination growth is not always stable and because the specimen cannot simply be adjusted in the loading fixture to obtain data from different delamination lengths. Because a compliance calibration technique would be difficult to perform, the calculation of toughness from an MMB test relies on closed-form equations. Because the MMB test combines the DCB and 3ENF tests, the closed-form equations for displacement and strain energy release rate for these tests, which have already been presented in the previous sections, will be used to calculate the displacement and the G for the MMB test. It has been shown that the applied load from the MMB test can be used to calculate equivalent DCB and 3ENF applied loadings as follows [14]:

$$P_{DCB} = \frac{(3c - L)}{4L} P_{MMB} \quad P_{ENF} = \frac{(c + L)}{L} P_{MMB} \quad (15)$$

Likewise, the displacement measured during the MMB test has been shown to equal a combination of the displacements from the DCB and 3ENF tests.

$$\delta_{MMB} = \frac{(3c - L)}{4L} \delta_{DCB} + \frac{(c + L)}{L} \delta_{ENF} \quad (16)$$

Substituting Eqs. 15 into Eqs. 7 and 11 and then substituting the resulting equations into Eq. 16, the following expression for displacement for the MMB test can be derived:

$$\delta_{MMB} = \frac{4(3c - L)^2(a + \chi h)^3 + (c + L)^2[3(a + 0.42\chi h)^3 + 2L^3]}{96 L^2 \left(E_{11} \frac{bh^3}{12}\right)} P_{MMB} \quad (17)$$

with doublers \rightarrow

$$\left[4\beta(3c - L)^2(a + \chi h)^3 + (c + L)^2((4\beta - 1)(a + 0.42\chi h)^3 + 2L^3) \right] \frac{P_{MMB}}{96 \beta L^2 EI_{del}}$$

Substituting Eq. 17 into Eq. 1 the following equation for G is derived:

$$G = \left[4(3c - L)^2(a + \chi h)^2 + 3(c + L)^2(a + 0.42\chi h)^2 \right] \frac{P_{MMB}^2}{64 b L^2 \left(E_{11} \frac{bh^3}{12}\right)} \quad (18)$$

with doublers \rightarrow

$$\left[4\beta(3c - L)^2(a + \chi h)^2 + (4\beta - 1)(c + L)^2(a + 0.42\chi h)^2 \right] \frac{P_{MMB}^2}{64 \beta b L^2 EI_{del}}$$

Eq. 18 could also be derived by combining Eq. 9 and 12 using the following equation.

$$G = G_I + G_{II} \quad (19)$$

To produce more accurate results, the ASTM standard requires that the bending stiffness be back calculated from the measured compliance, C , from the test. The compliance is simply the reciprocal of the slope of the load displacement curve. The following equation is derived from Eq. 17:

$$\left(E_{11} \frac{bh^3}{12} \right) = \frac{4(3c-L)^2(a+\chi h)^3 + (c+L)^2[3(a+0.42\chi h)^3 + 2L^3]}{96 L^2 C} \quad (20)$$

with doublers \rightarrow

$$EI_{del} = \left[4\beta(3c-L)^2(a+\chi h)^3 + (c+L)^2((4\beta-1)(a+0.42\chi h)^3 + 2L^3) \right] \frac{1}{96\beta L^2 C}$$

In the data reduction for the MMB test, each equation must be adjusted for the use of the doubler plates, but once the doubler parameter β is calculated, the changes to the data reduction equations are minor.

DEMONSTRATION PROBLEM

The fracture toughness of a carbon-carbon composite was measured. The material consisted of a 3K tow, 8-harness satin weave preform, made from T300 fiber, which was impregnated with an ACC6 precursor matrix before being pyrolyzed. An initial delamination halfway through the thickness of the specimen was created by an ash layer. Normally, an initial delamination is created with a thin nonadhering film insert, such as Teflon, but in this case the high manufacturing temperatures of carbon-carbon would have ruined the insert. The ash layer extended 2 inches in from one end of the specimen. The specimen was only 0.09 inches thick. When the first MMB test was performed at a G_{II}/G_I ratio of ~ 0.4 ($c/L = 1.06$), the top arm of the specimen failed in bending before the delamination grew, as described in the introduction. To overcome this problem, 0.04-in.-thick aluminum doubler plates were bonded to the top and bottom surfaces of the remaining specimens. Three specimens with doublers were tested for mixed-mode fracture toughness. The load-displacement records from the tests are shown in Figure 6. There was no sign of damage occurring before the delamination growth occurred. The test parameters are shown in Table 1, and the test data from the three specimens are shown in Table 2.

There is a large amount of scatter found in the initiation toughness values, which were measured from the point when delamination growth was observed on the edge. This is most likely due to the nonstandard insert (the ash layer) not providing a uniform delamination front. As the delamination

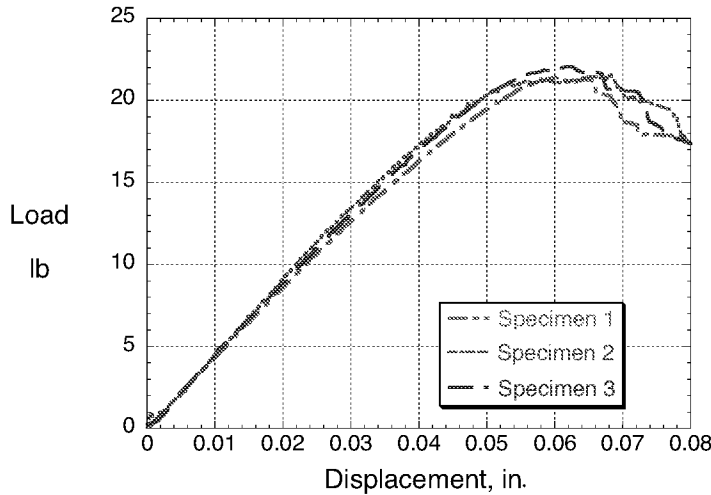


Figure 6 Load-displacement curves from MMB tests with doubler plates.

Table 1 Test Parameters

Parameter	Value
h_D	.0393 in.
L	1.969 in.
b	1.003 in.
c	2.08 in.
E_{11}	12.2 Msi
E_{22}	12.2 Msi
G_{13}	4 Msi
Γ	3.6
χ	0.70

Table 2 Experimental values

Spec.	h	β	C	EI_{del}	a_{init}	P_{init}	G_{init}	G_{prop}
	in.		in./lb	lb-in ²	in.	lb	in-lb/in ²	in-lb/in ²
1	0.0858	0.95	0.00209	529	1.024	13.3	0.19	0.70
2	0.0900	0.95	0.00196	592	1.063	12.1	0.15	0.77
3	0.0860	0.95	0.00206	516	0.984	9.3	0.08	0.71
Average				545			0.14	0.72
COV				7.4%			39.8%	5.2%

grew, the toughness values increased significantly, and the values became stable after approximately 1/3 inch of crack growth. The propagation toughness values reported in Table 2 are the average of three toughness measurements taken in this plateau region. These values are very consistent, having a coefficient of variation of only 5.2%

DISCUSSION

The use of doublers allowed the fracture toughness to be measured from specimens that would otherwise have been unusable. The technique may prove useful for testing materials that only come in thin sheets or where the properties of the material are suspected to change when the material is manufactured in thicker sections. The technique may also be used to test very tough materials such as specimens that contain through-the-thickness reinforcement. With very tough materials, specimens of normal thickness would still have the arms fail in bending before delamination growth occurs. Thicker specimens could be manufactured for these tough materials to reduce the bending stresses but only up to a limit set by the individual test standards. The limits are imposed because the equations used to calculate toughness from experimental measurements are all based on beams in bending. With very thick beams, the deformation of the specimen is no longer dominated by bending. By bonding high strength doublers to the composite specimen, the required strength may be obtained while keeping the specimen acceptably thin. Using doublers might also be used to salvage a group of specimens which were manufactured to a given thickness before it was realized that there would be a problem with a bending failure of the specimen arm.

Bending failure is not the only problem that can be solved with the use of doublers. Each test standard imposes a limit on the applied displacement. Beyond that limit, geometric nonlinear effects invalidate the data reduction methods. High modulus doublers can be used to increase the specimen stiffness so that the limit on applied displacement is not exceeded.

When using doublers, one must still insure that damage does not occur before the delamination grows. Damage may come in the form of yielding of the doubler material, failure of the bond between the composite and the doubler or tension failure of the composite, and would normally occur near the crack tip where the stresses are highest. Any of these failure modes, which may be observed visually or may be evident from the load-displacement record, would invalidate the test data. When choosing a doubler material, the following parameters must be considered:

- (1) The modulus must be high enough so that the overall specimen does not need to be made too thick
- (2) The thickness should be thick enough to provide the needed stiffness but not so thick to exceed test limits
- (3) The yield strength should be high enough so that the delamination grows before the doubler yields.
- (4) The bond strength between the doubler and the composite must be sufficient to remain undamaged during the test.

CONCLUSIONS

Doubler plates were bonded to thin composite delamination specimens as a way to delay bending failure of the arm of the test specimen, so that delamination fracture toughness measurements could be obtained. The doubler cantilever beam (DCB), end notch flexure (3ENF), 4 point ENF (4ENF) and mixed-mode bending (MMB) tests were considered. The effect of the doublers on the data reduction methods was examined for each test. Often the use of doubler plates required no change at all to the data reduction procedures. When changes were required, the changes were minor once a doubler parameter, β , was calculated, which describes how much the doubler plates changed the ratio of bending stiffnesses of the full thickness and delaminated beams. The use of doubler plates was demonstrated by testing the mixed mode toughness of a carbon-carbon material using specimens that would have otherwise failed in bending before delamination growth occurred. The use of doubler plates may be useful in many situations where problems are encountered when testing with ordinary delamination specimens.

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